



LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

Adventures in Laser Produced Plasma Research

M. Key

February 7, 2006

Inertial Confinement Nuclear Fusion: A Historical Approach by
its Pioneers

This document was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor the University of California nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or the University of California, and shall not be used for advertising or product endorsement purposes.

ADVENTURES IN LASER PRODUCED PLASMA RESEARCH

Introduction

In the UK the study of laser produced plasmas and their applications began in the universities and evolved to a current system where the research is mainly carried out at the Rutherford Appleton Laboratory Central Laser Facility (CLF) which is provided to support the universities. My own research work has been closely tied to this evolution and in this review I describe the history with particular reference to my participation in it.

1. Laser produced plasma research in the UK prior to the advent of the Central Laser Facility (1962 to 1975)

The invention of the ruby laser in 1960 and the technique of Q switched generation of megawatt pulses in 1963 initiated the study of laser produced plasmas .

Graduating in physics in 1962 at the Imperial College (IC) of London University. I joined the IC plasma physics research group as a PhD student . The group's tradition was that the first task of a new student was to find his or her own research topic. The plethora of research information at first seems overwhelming and disordered. My path to somewhat coherent thought was helped by a coffee break conversation with Malcolm Haines, then a young lecturer, who suggested that Thomson scattering of laser pulses newly being investigated at the UKAEA Culham Laboratory for diagnosis of magnetically confined plasmas, might provide a research topic . Three years later having designed and built my own Q switched ruby laser, small theta pinch plasma and high luminosity optical spectrometer, I completed my PhD studies of Thomson scattering.

Looking for employment I saw a post doctoral position advertised by Dan Bradley, another lecturer at IC specializing in laser research. The position offered was to study the new topic of ionizing effects of laser radiation. I applied and my job interview was conducted in a casual meeting with Dan as we shared a lift from the ground floor of the Physics department . Before we reached my lab on the 7th floor he offered and I accepted the position .

Dan was moving fast in his research and when I joined his team in Oct 1965 he had already been promoted to a readership at another college of London University, the Royal Holloway College(RHC) . My immediate goal at RHC was to build a more powerful Q switched ruby laser to produce gas breakdown and to cooperate in measurement of the plasma formation with Shampana Majumdar another post doctoral member of Dan's team, who was developing a nanosecond electronic framing camera. In our first year we made laser induced gas breakdown plasmas and imaged their explosion with the framing camera.

Dan's career progress was stellar and during that first year at RHC he announced that he was moving in Oct 1966 to Queens University Belfast (QUB) as a full professor and

head of the Physics Department . He suggested that I apply for a lectureship at QUB. This was an offer I could not refuse, a tenured job less than 1 year after my PhD. Before the move to Belfast I was distracted somewhat by the planning and execution with Imperial College friends, of our second Royal Geographical Society sponsored mountaineering and glaciology expedition to the Stauning Alps of East Greenland. While Dan was managing the move of his research team to Belfast I was preparing supplies for our parachute drop and took an 8 week summer vacation for the expedition to Greenland. Dan was not amused.

Newly appointed at QUB in Oct 1966 I had the opportunity to set up my own research group . Nd glass had become a technically better option for high peak power. After retrofitting my ruby laser equipment with Nd glass, I obtained funding and set about building a new multi- gigawatt Nd glass laser facility. Building a laser in the university environment meant getting your hands dirty and on this occasion involved tasks as mechanical as winding inductors and wiring capacitor banks. While continuing to study gas breakdown plasmas, I became interested in laser interaction with solid targets, particularly the associated emission of x-rays and we made some of the first measurements of x-ray spectra by Bragg crystal diffraction. I recall Dan saying that with such bright x-ray line spectra it should be possible to make an x-ray laser. When I argued that it was not that simple his response was unsympathetic - there must be a way. Later he would be proved correct.

I became interested in x-ray laser research and started experimental study of laser produced recombinant CVI plasmas. This was a scheme first suggested by Russian researchers and the only one that was amenable to experiments with modest sized lasers. At that time it was being researched also by Geoff Pert at the University of Hull . Geoff and I graduated together , both did our research in the IC plasma physics group and were friends and partners in the Greenland expeditions. Geoff would later be a leading university user of the CLF and chairman for several years of the Laser Facility committee over seeing the work of the CLF .

Taking advantage of Dan's pioneering of picosecond optical streak cameras through use of high extraction field at the photocathode to improve time resolution , I decided to develop an x-ray streak camera. This was a case where Dan was skeptical because the key time resolution issue in optical streak cameras was the transit time spread due to the significant fraction of 1eV spread of photoelectron energies. He pointed out that x-ray photo-ionization would produce keV electron energy spread. Luckily it turned out that secondary cascade effects inside a solid photocathode moderate the escaping electron energy spread to a few eV and the x-ray streak camera gave resolution down to 10 ps . Its first application was in studying the temporal evolution of population inversion in the CVI resonance spectrum of a recombining plasma.

By this time laser research at QUB was at the forefront in the UK and also internationally recognized, particularly for Dan Bradley's pioneering work on mode locked dye lasers. The Nd glass laser in my group was then the most powerful laser in the UK . In 1969 we organized a conference on non -linear optics, which was internationally well attended

notably by Nikolai Basov, despite its coincidence with the re-emergence of sectarian conflict and barricades in the streets of Belfast. In 1972 I was promoted to senior lecturer.

The emerging concept of laser fusion motivated strong interest among UK academics active in laser plasma studies. Notable among them was Stuart Ramsden who had made some of the first studies of laser induced gas breakdown in Canada. On returning to the UK to set up the Applied Physics Department at the University of Hull, he had established a strong laser plasma research team emphasizing CO₂ lasers which complemented the activity at QUB. Geoff Pert was one of his young lecturers beginning a career which would later establish him on the world stage as a leader in numerical modeling of x-ray lasers .

It was becoming too difficult for individual UK universities to compete in laser plasma research, with major laboratories world wide. A committee of senior UK academics chaired by Dan Bradley and including Stuart Ramsden, was formed to discuss setting up a national high power laser facility. My involvement was vicarious, as a young expert backing up Dan Bradley by producing required technical information. Dan was arguing to have a national facility at QUB but his case was undermined by the continuing sectarian conflict in Belfast. Eventually it was agreed that it would be better to build a facility at the Rutherford Laboratory, which then provided mainly accelerators for UK university research in high energy nuclear physics. [The RL was an outgrowth of the Harwell Atomic Energy Research Establishment . Initially AERE was a partner in the plan but later dropped out] . The superior engineering capabilities of a large laboratory were seen as an important advantage. The first laser produced thermonuclear fusion demonstrated at KMS fusion in 1973/4 further stimulated enthusiasm for a new facility.

In 1973/4 I took a year's sabbatical leave as a Humbolt and Royal Society Fellow at the Max Planck Institut fur Plasma Physik in Germany. The laser facility there was equipped with the leading Nd glass amplifiers from the French Cilas company . Working under Siegbert Witkowski with Richard Sigel and Klaus Eidmann I studied high intensity laser interaction with deuterium ice. I also spent a large fraction of my time there working on x-ray laser design concepts which I summarized in an invited talk at a US Gordon conference, giving some of the early estimates of possibilities for recombinant , collisionally excited and photo-ionized lasers .

Technical design work for the proposed new facility began at the Rutherford Laboratory led by Paul Williams, then an experienced experimental scientist coming from accelerator physics bubble chamber research. The chief engineer was John Boon who had worked with Paul on bubble chambers. I was their technical advisor on lasers and laser produced plasmas and in 1974 we toured US labs to assess the state of the field and the laser technology options.

2. Work at the Central Laser Facility 1975 – 1996

Formal approval and funding of the Central Laser Facility (CLF) project by the Science Board of the Science Research Council (SRC) was obtained in October 1975. This source meant that the CLF was funded by a committee of senior university staff in competition with all other demands for university research and was seen as an element of the overall support for university science. The mission of the CLF was to provide high power laser facilities for UK university research.



Figure 1 Left to right Prof. Alan Gibson, Prof. Dan Bradley, Sir Sam Edwards (SRC chairman) and Godfrey Stafford (RAL Director) at the inauguration of the CLF

2.1 The early years of the Central Laser Facility led by Alan Gibson (1975 to 1983).

Alan Gibson who had been the founding head of department at the new physics department at the University of Essex , was appointed to lead the CLF with Paul Williams as his deputy . Alan was greatly respected by the whole community and gave the CLF excellent early leadership. He was an established scientist in solid state physics and lasers and I very much enjoyed working with him, for instance when we jointly wrote a review paper on high power lasers covering Nd glass , CO₂ and Iodine lasers ¹.

The design of the new laser facility crystallized around the best available rod amplifiers from the Quantel company in France and new disc amplifier technology developed at the US Lawrence Livermore Laboratory and offered for sale by ILC Inc. A design with a single beam line of Quantel rod amplifiers branching to two- beams with ILC disc amplifier output was adopted. The single beam section came into operation first generating 100 GW in 100ps and the first laser produced plasma experiments were conducted in Dec. 1976 . Two 10.8 cm ILC disc amplifiers were then added bringing the power in two beams to 800GW in 100 ps. The first two beam implosion experiments were carried out in April of 1977 . The rapid start was facilitated by using existing buildings at the Rutherford Laboratory.

In 1976 I was promoted to a Readership by QUB and seconded to the CLF with the initial task of coordinating the scientific program of two beam laser compression of matter, with Tom Hughes from Essex university performing the same function for single beam laser plasma interactions. We organized the experiments with participation of the

whole community . Subgroups worked on specific types of diagnostic instruments . In that way we made a rapid start on the science with contributions from 20 institutions including the universities of Belfast , Essex, Hull, Imperial College ,Oxford, Royal Holloway College , Glasgow , St Andrews and Swansea . In the start up phase there was no formal schedule of operations. Instead there was ad hoc alternation between two beam compression studies, single beam interaction studies and laser maintenance,

The program was overseen by a Laser Facility Committee (LFC) whose members represented the university users . In addition to its oversight of the work of the CLF the committee reviewed and funded 3year research grant proposals from university researchers. Funding the research of the users was a key reason why the facility was successful.

Through the LFC we initiated a glass laser scientific program and scheduling committee in 1978 and re-organized the community into scientific topic groups each with a scientific convenor and CLF staff secretary . These were ; atomic and radiation physics (Brian Fawcett), xuv lasers and harmonic generation (Nick Peacock), ablative compression (Tom Hall), laser plasma interactions (Tom Hughes) transport and particle emission , (Joe Kilkenny) , theory and modelling ,(Malcolm Haines) and facility development, (Paul Williams) . Only the facility development group had a CLF staff member as its leader and the convenors of the groups served short terms allowing participation in the science leadership to be widespread in the community. The groups prioritized their ideas and the scheduling committee determined the allocation of laser time . CLF staff were non voting members in scheduling decisions. This method of working made the CLF very different from for example national laboratories in the USA. The research was driven by the university user community not the laboratory staff. The goals were pure science with no links to defense activities. In the UK all classified atomic weapons related science is conducted separately at the Aldermaston laboratory(AWE) .

My own research group from QUB was a strong participant in the science with Ciaran Lewis who would go on to succeed me as plasma group leader at QUB, playing an increasing role . We developed miniature space resolving x-ray crystal spectrographs to separate the implosion core and shell ablation plasma spectra in micro-balloon implosions. We fielded an improved x-ray streak camera and used it with pinhole camera imaging to record implosion times and with x-ray crystal spectroscopy to make the first streak resolved x-ray spectra. We initiated the first x-ray backlighting and demonstrated this with x-ray pinhole camera imaging of an implosion backlit by a second laser produced plasma shown in figure 2 . This work was extended to include the first streaked backlighting of an ablative implosion trajectory. I was interested in implosion physics and worked with a Canadian sabbatical visitor Boye Ahlborn, on analytic modeling of exploding pusher and ablative implosions.

Through Alan Cairns of St Andrews university the Scottish University Summer Schools in Laser Plasma Interactions were started. The first was in 1979 and the proceedings covering the whole field of laser produced plasmas , were published by the University of

Edinburgh and comprised one of the earliest summaries of the science . My contribution was a review of the physics of energy transport and laser compression of plasmas.

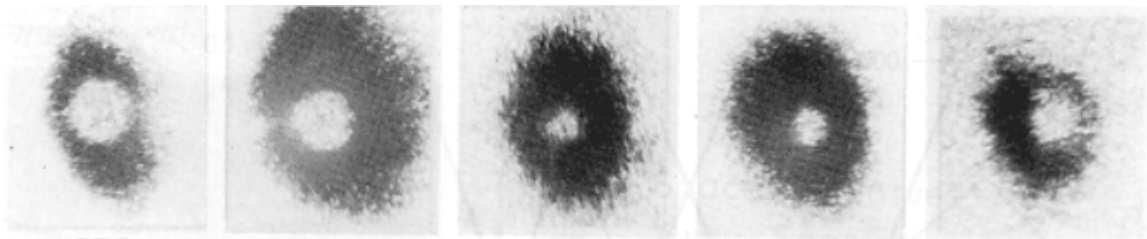


Figure 2 The first x-ray backlighting radiography (laser driven implosion of a 70 μm diameter glass micro-balloon- images at delay times relative to the 100 ps pulse irradiation of the micoballoon, of 250, 350, 450, 570 and 670 ps)

The spectroscopy and streak camera work by my QUB group became collaborative with IC where Dick Lee and Joe Kilkenny were very active young staff members . Dick provided advanced line broadening calculations and Joe was beginning his rapid rise to prominence as an experimental scientist in ICF research. He went on to setup the Kentech company with John Hares which became the lead manufacturer of x-ray streak and gated channel plate cameras. Later he joined the US Lawrence Livermore National laboratory where he advanced to program leader for Inertial Confined Fusion (ICF)and the National Ignition Facility (NIF). My interest in x-ray spectroscopy of laser produced plasmas was the basis of a review paper I published in 1979 with Richard Hutcheon² .

The good cooperation between QUB and IC led to the first use of K-alpha emission to estimate energy transport by hot electrons, to the first streak radiography of the growth of Rayleigh Taylor unstable ripples and to backlit x-ray images of RT growth features on imploding microballoons. We also studied laser ablation at both first second and third harmonic frequencies using streaked x-ray spectroscopy to show layer burn through times. Energy transport and ablation pressure became a significant theme in my work which I summarized later in a chapter of the Handbook of Plasma Physics in 1991³. A related advance in transport theory was the first Fokker Planck model explaining the enigma of heat flux limits, developed by IC's Tony Bell and Roger Evans and Dennis Nicholas at RAL.

The output of novel science by the numerous early phase users of the CLF was substantial and it is not possible to adequately credit it all in this short review . Examples include measurements and modeling by Lawrence Wickens , Phil Rumsby and John Allen which greatly advanced the understanding of fast ions and the observation of filamentary heat flow instabilities in elegant optical probe measurements by Oswald Willi.

Target fabrication was a CLF responsibility most ably managed by Phil Rumsby. With Malcolm Gower he pioneered the use of excimer laser ablation for micro machining of for example 10 micron scale grooves in polymer micro-balloons to initiate RT instability as shown in figure3. He also facilitated some of the first research by visiting medical

researchers studying UV ablation of the cornea of pigs eyes which was a precursor of modern Lasik treatment . Malcolm launched an independent excimer laser UV lithography project , a technique which later became the major method of microelectronic chip fabrication .

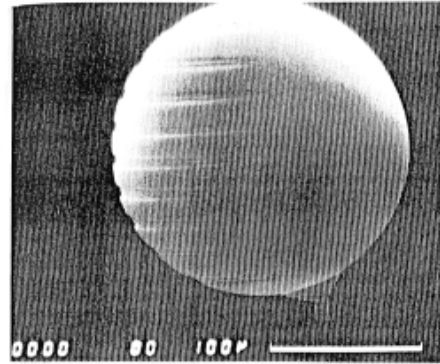


Figure 3 Right: Polymer microballoon with excimer laser formed grooves . Left:Exitech laser system for producing ink jet printer nozzles

My role changed first to one of overall science coordination for the glass laser experiments in 1978 and then in 1979 I resigned from Queens University to take a staff position at the Rutherford Laboratory as the group leader for glass laser experiments . A few months later I became deputy head of the CLF taking over from Paul Williams when he became deputy head of the Rutherford Laboratory. Later he would become its director . I had only three years in my deputy role before Alan Gibson retired and I became the director of the CLF in 1983. My first task in my new job was to organize the community to fight successfully against threatened budget cuts which could have virtually closed down the CLF.

2.2 The history of facility development at the CLF

Facility development was a constant activity at the CLF . The goals were generally to increase the opportunities for novel science by enhancing both the versatility of the target irradiation capabilities and the available laser power. It was the prime responsibility of the laboratory staff – new objectives were approved by the LFC and when funding supplements were needed they were obtained through proposals to the Science Board of the SRC. We organized the work in phases with minimum disruption of operations.

Alan Gibson decided the glass laser should have a name for better public relations. Suggestions were sought and Vulcan was chosen (after the Roman god of fire and also a Latin acronym devised by Roger Evans ,Versicolor Ultima Lux Cohaerens pro Academica Nostra).

In 1980 the 2 beam laser was enhanced to six beams using Faraday rotator coupled output from 3 double passed 10.8 cm disc amplifiers , each of the three beams being split two ways on a 50% reflecting mirror . The new disc amplifiers were designed at RAL by Ian Ross with improved N₂ cooling for higher shot rate and phosphate glass was used . The building was extended to accommodate larger capacitor banks and a disc amplifier

handling clean room . A new six beam target irradiation facility was constructed. The system was operated with remote controlled sliding mirrors to feed shots alternately to the two beam and six beam chambers allowing two experiments to run in parallel giving a significantly higher number of laser shots for experiments . Annual shot counts on targets approached 2000.

A novel aspect of the Vulcan upgrade made it the first laser to have a dedicated auxiliary beam for x-ray backlighting and single beam interaction studies . The new system included synchronized mode locked and pulse sliced oscillators to allow independent short and long pulse shapes for the main beams and the back-lighter beam .

Next the power of the six beam system was increased by adding 3 more output disc amplifiers to eliminate the need for beam splitting . The feeder chain was given more output to allow single pass operation of the output amplifiers, thereby avoiding damage to the faraday rotator polarizers and generating up to 1.2 kJ . Second harmonic green light operation was provided making the CLF the first laser facility to be equipped for green light driven implosions.

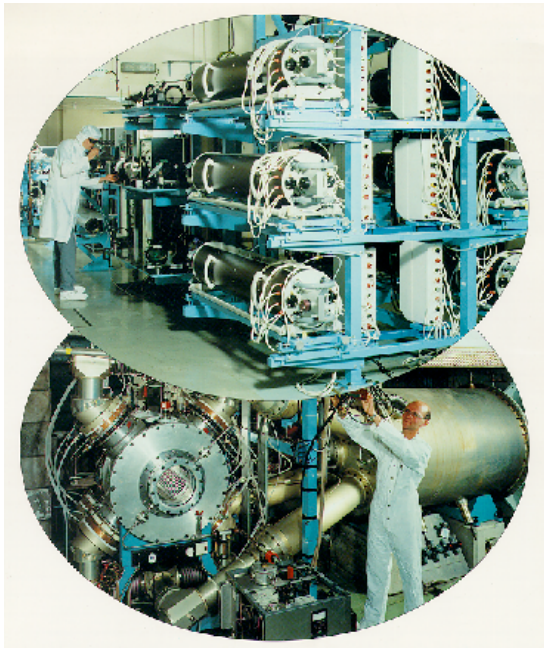


Figure 3 The Vulcan six beam Nd glass amplifiers generating 1.2 kJ, 1ns at $1.05\ \mu\text{m}$ and the Sprite KrF amplifier (200J,60ns 0.248mm) and 1TW pulses in 300fs (CPA) and 10 ps (Raman)

A major target area upgrade was begun in 1983. The laser building was extended again to add two new target irradiation laboratories, while retaining the original two beam target chamber. A new implosion facility TAW used mirror splitting of the six beams to give 12 beams at 2w for improved symmetry and efficient ablative drive . It came into operation early in 1985 . A new concept for the second laboratory TAE , used an original

idea of Ian Ross to create a high quality six beam astigmatic line focus for x-ray laser research using in each beam off axis spherical mirror imaging of a high quality beam focus produced by an aspheric lens . This configuration included an option to change to a unidirectional six beam cluster focus for concentration of energy on planar targets or into a hohlraum . The pulse generators were constantly under development with several available options operated in parallel– for example two frequency operation for beat wave acceleration experiments.

Colin Danson joined the CLF from the Aldermaston laboratory and gave important impetus to operation and development of Vulcan ,first working under Chris Edwards and then taking on the responsibility himself. The laser system was completely rebuilt in 1989 – improved rod amplifiers were added – new disc amplifiers of improved box design were installed and the auxiliary beam was upgraded by splitting it into two parallel arms and boosting the total energy to 1 kJ with two RAL developed 15 cm disc amplifiers illustrated in figure 4.

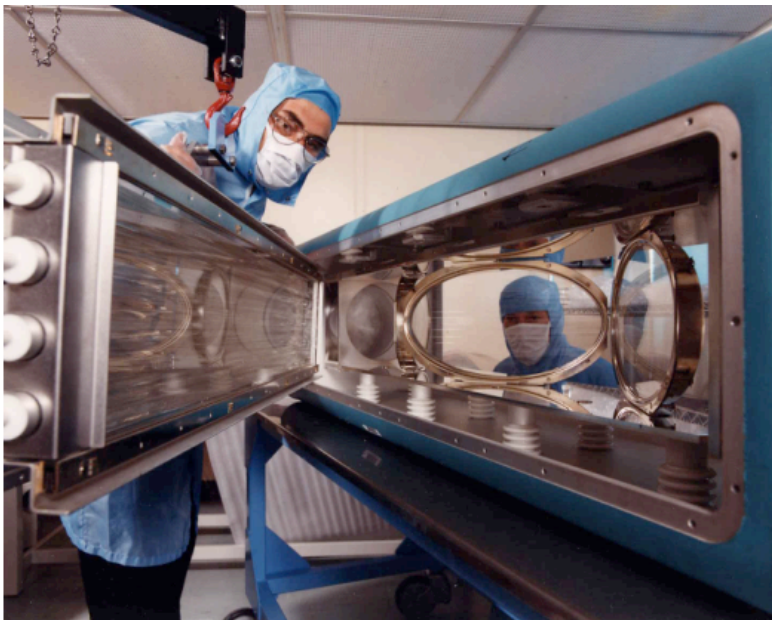


Figure 4 CLF developed 15 cm box type disc amplifier

Alan Gibson had initially introduced both CO₂ laser and excimer laser R&D at the CLF . The CO₂ work was soon phased out but Excimer laser development initiated two new branches of activity . Excimer UV pulses were of interest for photochemistry and starting with narrow band tunable excimer radiation pioneered by Malcolm Gower , this led to a branching out to provide a UV radiation facility (UVRF) for photo chemistry . The UVRF progressively evolved into a wide range of short pulse frequency tunable lasers for photochemistry and photo biology in the Laser Support Facility (LSF) – an activity which continues today quite independent of the laser plasma studies with high energy lasers .

The second branch was relativistic electron beam pumped excimer lasers, where Fergus O'Neill and Mick Shaw first developed an electron beam pumped KrF laser ELF using an oil pulse forming line. This led on to a much more sophisticated higher energy KrF laser Sprite, so named because it was a water ELF using water insulated pulse forming lines. Sprite had 4 pulse forming lines feeding electron beams from 4 sides of a 25cm diameter 1 m long cylindrical gas cell. Coming into operation in 1983 it first generated 200J, 50ns, 248 nm UV laser pulses with 10% e-beam to laser efficiency an oscillator.

Sprite was an R&D project aimed at order of magnitude higher efficiency than the glass laser and high brightness UV beams. It was used to pioneer a Raman laser concept in which a methane cell Raman amplifier was pumped by multiple KrF laser beams derived from Sprite by angular multiplexing. Short duration pulses in angularly separated beams sequentially extracted the KrF laser energy at 2 ns intervals corresponding to the energy storage time. A single 10 to 40 ps pulse at the 268 nm Raman shifted wavelength, was injected into the Methane cell co-propagating with the time coincident multiplexed KrF beams reflected at small angles from the walls. High Raman gain caused up to 50% efficient saturated Raman amplification. Energy was transferred to the high quality Raman beam irrespective of the beam quality of the pump beams. The Sprite Raman laser generated 10J, pulses with near diffraction limited quality at powers up to 1 TW. I also initiated work to make Sprite the first KrF laser to be adapted for CPA operation with a single chirped pulse being amplified then compressed to 0.3 ps giving up to 1TW peak power. The CPA project was carried out by Ian Ross. The system was equipped with its own target irradiation chamber and was operated intensively for users experiments at novel UV high intensities and short pulse durations.

The KrF laser development became linked to efforts to launch a European Laser Facility (also called ELF). Europe has a long tradition of sharing scientific facilities such as CERN and ESA. In 1988 Bill Mitchell was the research council (SERC) chairman. He was persuaded that ELF was a timely concept. Bill had support from the Science Board and lobbied the other heads of European Research Councils and they jointly agreed on a formal study by a Scientific and Technical Working Group. The national research councils of UK, France, Italy, Germany and Spain participated and each nominated two members of the ELF Working Group. It was jointly led by Fritz Schafer for Germany, Edouard Fabre for France and myself for the UK. It included A Migus, S Witkowski, A Caruso, T Letardi, M Vasselli, J Orza, J Campos and G Pert. Meetings were held in each of the participating countries and we made a detailed technical study of KrF and glass laser concepts and their scientific applications. I was strongly committed to the idea of ELF and personally put heavy technical and organizational work into the study.

At this time a review of the CLF by a Science Board appointed committee chaired by Professor Laurie Challis resulted in recommendation of aggressive development of the new KrF laser technology in parallel with participation in the ELF initiative. The vision was that ELF should be a pure science facility independent of the defense linked ICF work in the USA and France. The KrF R&D at the CLF would provide the technical basis for inclusion of a KrF Raman system in the ELF project and ELF would take over the KrF development. I reorganized the structure of the CLF into an operations division

headed by Bill Toner and an R&D division emphasizing KrF which I headed, to reflect the new policy. We put considerable effort into technical evaluation and design of KrF CPA and Raman concepts for ELF. There was a down side in that we had to cut the funding for the glass laser which was unpopular with the users.

The 1990 report on the European High Performance Laser Facility was a two volume document , the second being a large technical appendix. It was discussed with the potential user community at a European workshop in Frankfurt in Dec 1989. The gestation process had been difficult because of the divergent motivations of the participating countries and underlying tension with the Euratom policy of emphasis on MFE and a watching brief on IFE . The Euratom policy was a political compromise linked to the European mix of nuclear powers and countries with embargoes on nuclear weapons research and also to vested interests in the dominance of MFE research . The ELF project had to avoid direct commitment to fusion energy and be directed to basic research . There was much debate about whether or not to mirror the high energy Nd glass laser work at LLNL in the USA directed towards ignition . Our compromise recommendation was for a phased plan . First a one year design study then in Phase 1, a 30 kJ , 25 TW UV glass laser for experiments , an R&D project to generate 13kJ,100TW of KrF Raman output. a 1PW CPA glass laser and a 1PW CPA KrF laser for experiments . In Phase II starting four years later , a 100kJ UV facility would be constructed using the preferred choice between glass and KrF. When the report was considered by the sponsoring European research councils ,the underlying conflicts surfaced. In the UK it coincided with a funding crisis for the SERC and UK participation was formally abandoned. The ELF initiative had failed.

One bright note on the European front was the inclusion in 1990 of the CLF in a European network of laser facilities which opened access to European users with EU funding of their laser shots .

Faced with a difficult post ELF situation I was convinced that the best future path at the CLF was towards high intensity with short pulses. There was no way to compete in high energy lasers with the available resources . After extensive consultation with the facility users a new plan was formed to provide CPA operation of Vulcan and an enhanced KrF laser Titania with both CPA and Raman short pulses .

Glass laser CPA motivated by the discoveries of Gerard Mourou, provided a relatively low cost low risk means to increase the power of glass lasers by factors of the order of 100x by reducing the pulse length to less than 1 ps . A new project was launched and the TAW 12 beam target irradiation facility was replaced by a six beam system with flexible geometry and a single CPA beam line. The CPA beam was one of the twin 15 cm beams and produced grating compressor limited 40J pulses . The project was ably led by Chris Edwards and Colin Danson with Ian Ross providing the R&D basis .

Titania was a more ambitious project led by Mick Shaw. It involved building a much larger 40 cm diameter electron beam pumped KrF amplifier module capable of 1.5kJ in 170 ps in free running output . It was designed for incorporation it into an expanded

angular multiplex system with Sprite as a pre amplifier, the whole system feeding a multi-stage Raman amplifier culminating in a 15 cm square methane cell . New funding was needed for Titania and it was provided through a proposal to the Science Board . The Titania system was built as planned and included target irradiation capability provided for both the CPA and Raman outputs.

The Titania multiplexed Raman system was challenging . The scale up from Sprite was considerable and the very long multiplexed KrF beam paths needed for the 4x longer e-beam excitation of Titania led to beam quality degradation due to air turbulence, prompting Mick Shaw to go to the extreme of even contemplating a He filled multiplexing hall ! Competing non -linear effects in the Raman system also threw up some problems which limited conversion efficiency in the final amplifier. It needed significant R&D effort to realize its potential.

With hindsight it is clear that my advocacy of both advanced short pulse KrF and glass CPA technology in the post ELF discussion was over optimistic. It was bound to overstretch the resources of the CLF in the absence of a European commitment. CLF funding was almost a zero sum game. The Science Board was happy with its level of investment but would not significantly increase it. The post ELF KrF Raman work was high risk because without ELF there was not a strong international effort. The Ashura project in Japan was the only other large scale KrF Raman laser project. The point was reached where hard choices were required – either commit most R&D effort to KrF starving the glass laser CPA development or abandon KrF. The choice was difficult because glass laser CPA was immediately advantageous to facility users whereas the KrF Raman laser had longer term potential for novel capability. The users would not tolerate any cut back of glass CPA development which we therefore continued, and R&D funds for Titania were consequently insufficient, leading to a slow decline and eventual close down of Titania. This occurred in 1998 two years after my departure from the CLF. Mick Shaw seeing his dream fade away, took early retirement to a farm in Wales.

The glass CPA work prospered. The new TAW facility with its 40J,1ps CPA beam produced novel science and enthusiastic support of the users. An upgrade to 80 J operation was implemented by increasing the compression grating aperture.

An ambitious 1 PW upgrade of Vulcan was negotiated by Henry Hutchinson and approved in 1998 . It was implemented with another major building extension housing the compressor vessel and target irradiation chamber . The upgrade was assisted by supply of 1m diameter compression gratings and 20 cm amplifiers from surplus LLNL Nova parts , in exchange for which LLNL was allocated future access to the laser . The facility came into operation in 2003 . A related notable R&D advance was Ian Ross's pioneering work on optical parametric chirped pulse amplification (OPCPA), which is now the preferred front end technology for PW lasers worldwide and is used to good effect in the CLF's PW laser . OPCPA was an outgrowth of work for the LSF to produce twin beam frequency tunable picosecond pulses for photo chemistry using parametric amplification .

The RAL PW laser has proved to be a very successful facility supporting a wide range of novel high intensity science . A planned upgrade will bring a synchronized high energy long pulse beam line from 20 cm disc amplifiers into the PW interaction chamber.

Henry Hutchinson also successfully promoted the addition in 1998, of a rep rated Ti Sapphire laser Astra, to the CLF's suite of lasers for plasma physics. Astra provides CPA pulses up to 1 J in 50 fs at several Hz supporting a range of experiments . It is currently being upgraded to twin beam operation and PW power.

2.3 Science at the CLF (1983 to 1996)

Taking over from Alan Gibson in 1983 I was to lead the CLF for the next 13 years . Phil Rumsby had had wide experience in managing target prep, experimental target areas and the glass laser and when I took over from Alan Gibson I made Phil my deputy. He later went on to an outstanding career as an entrepreneur . His interest in excimer laser micro-machining led him to first take a sabbatical leave then to resign from the CLF in 1990 to found together with Malcolm Gower, the Exitech company which today has more staff than the CLF and is a highly successful business in all forms of laser micromachining (seefigure4). Bill Toner succeeded Phil as my deputy and also ably led the facility for the year before he retired (1994/5) when I took a sabbatical leave .

I was interested in resuming leadership of a university research group as a means to increase my involvement in plasma research consistent with the university based CLF scheduling system . In 1989 with sponsorship from Pat Sanders , the head of the Clarendon Laboratory at Oxford University , I was made a visiting professor at the Clarendon Laboratory and headed a research group there working closely with lecturer and college tutor Justin Wark and several PhD students.

After the new TAW 12 beam implosion facility and the TAE line focus and cluster focus target irradiation facilities were completed in 1984 and 1985 respectively the CLF entered its mature phase of science work. Up to 4 experiments could be prepared in parallel and two or three operated in parallel using TAW and TAE together with the old two beam target area and a small facility for higher rep rate shots using just the rod amplifiers.

The mature phase of the CLF saw much excellent work by the whole user community of Vulcan , Sprite and Titania . It is difficult to summarize work which produced an average of 40 Journal publications per year . Experiments were team efforts so mention of individuals gives credit only to the lead person(s). Some notable firsts included point projection space resolved absorption spectroscopy by Ciaran Lewis and x-ray line diffraction angle shifts in laser shocked crystals by James Lunney and Justin Wark. Absorption spectroscopy of K edge shifts and EXAFS measurements on laser produced warm dense matter were first made by Tom Hall . Schemes for smoothing laser speckle induced perturbation of ablation pressure were developed by Oswald Willi , I had continued my interest in ablative implosions using the 12 beam facility for several

objectives including collaborating with Troy Barbee to develop multi – layer mirror monochromatic x-ray imaging of layer burn through to assess ablation uniformity .

The Vulcan CPA beam at 40 then 100 TW was a fruitful source of new results .Laser generation of 50 MeV electron energies were measured in irradiation of solids by Bucker Dangor and IC colleagues. Scaling of hot electron temperature in 100 TW solid target interactions was estimated from fast ions and hard x-rays by Farhat Beg and Peter Fewes . Extreme magnetic fields >100Mgauss were measured by ingenious study of depolarization of harmonics by Karl Krushelnik. The shortest wavelength XUV high harmonics in solid target interaction were observed by Peter Norreys and Matt Zepf . Elegant laser accelerated proton beam probing of E and B fields was developed by Marco Borghesi and Andy MacKinnon. Peter Norreys became a significant influence in fast ignition research through his experiments at Vulcan and partnered with Ryosuke Kodama in the very successful first integrated fast ignition experiments in Japan.

In 1985 I was asked by the Editor of Nature to write a review of x-ray laser research ⁴ . XUV laser development was strongly boosted by the new TAE facility . We had formed an x-ray laser consortium and linking the teams from QUB, Essex and Hull (the latter led by Greg Tallents and Geoff Pert respectively) . We also had some notable young scientific visitors contributing to the work including Jie Zhang , now an academician in China and Ryosuke Kodama , now back at ILE in Japan where he has led the fast ignition experiments . Study of recombinant CVI and other recombination schemes studies was continued with the new facility but it proved impossible to obtain high enough gain length product to reach gain saturation and generate a strong beam . The first successful demonstration in 1985 of a collisionally pumped xuv laser using the neon-like ion of Se by Dennis Matthews and colleagues at LLNL motivated interest in collisional laser development using TAE . The LLNL work had used multi- kJ pulses from the Novette 2 beam laser . We did not have that level of laser energy but following a lead from work by Ray Elton and Tom McLean at the Naval Research Laboratory, and in collaboration with Tom McLean we demonstrated operation of a Ne- like Ge laser at 23 nm using much lower energy than the LLNL work . Further improvements led to saturated operation and further reduction of pump energy using double 100 ps pulse drive which made Ge our ‘volks laser’ as it was so easy to operate. We went on to develop a wide range of laser transitions with Ne –like ions and Ni-like ions , the latter allowing the shortest wavelength saturated operation down to 7nm in Ni-like Sm . We also studied control of the beams using generator amplifier schemes and measured beam properties such as coherence, and near and far field patterns and pulse duration . In 1987 I was lucky to be invited to spend a two month sabbatical at ILE Osaka working with Joshiako Kato and testing some ideas I had for shorter wavelength recombination lasers using the high energy UV beams of Gekko . The availability of CPA pulses in TAE led to further reduction of drive energy using the pre-pulse/short pulse transient gain scheme developed originally at the Max Born Institute by Peter Nickles . The general question of how to make the brightest XUV and soft x-ray sources using either lasers or high harmonic generation became interesting for me , particularly opportunities connected with use of the new intense UV laser beams of Sprite and Titania ,where I was also involved in the laser R&D.

With my Oxford research group using the Sprite Raman system and also the CPA beam (which had been the thesis topic of one of the Oxford students James Houlston) , we demonstrated high harmonic generation down to 6.7nm in a He gas jet in 1994 – then a short wavelength record - and studied field ionization of gases as a possible route to x-ray laser action by recombination to the ground state . We also investigated heating by very high flux density UV generated hot electrons which provided a link to subsequent work on fast ignition.

In 1996 I left RAL to join LLNL . Science at the CLF continued as vigorously as ever and I became an occasional user of the facilities as part of my work for LLNL .

3. My work at the Lawrence Livermore National Laboratory 1996 to present (Jan 2006)

Work at the Lawrence Livermore National Laboratory (LLNL) was on a larger scale than that of the CLF and LLNL became the world leader in high power and high energy lasers and their application in ICF . I had always had good links with researchers there. In 1975 the then Laser program leader John Emmett had offered me a senior staff position at LLNL and I had almost accepted. I declined eventually with the feeling that the CLF was an interesting challenge and that I owed the UK some more work having received a good and cost free education.

Almost 20 years later years later in 1994, Mike Campbell had succeeded John Emmett as LLNL Associate Director for the Laser Program leader and Joe Kilkenny was the Program Leader for ICF/NIF . Joe and Mike invited me to spend a sabbatical year at LLNL to coordinate work on direct drive ICF . I accepted the offer and was happy to revisit implosion physics and to use my x-ray laser background to carry out the first x-ray laser radiography of laser speckle induced hydrodynamic imprint on planar targets , a topical issue for direct drive . Luis Da Silva and Dan Kalantar were my key collaborators . I also joined in conventional backlit radiography studies of RT instability with Bruce Remington , Steve Weber and Gail Glendinning.

When I was on sabbatical at LLNL and enjoying the environment, they asked me to take a permanent job there . This was a radical proposition and on returning to the CLF I spent one year weighing the options, deciding to accept and obtaining a US residence permit. My main reason for moving to LLNL was that after 20 years at the CLF and 5 years before compulsory retirement at age 60 , a totally new job at LLNL was more interesting. It had more science and less management and no formal age cut off. NIF was being designed to achieve ICF ignition and the world's first PW laser was about to operate. The fact that our children had left home also made it easier to move. I returned to LLNL in Sept 1996 as deputy scientific director for ICF/ NIF . Henry Hutchinson who then headed laser research at IC was appointed to lead the CLF and has done that with an exceptionally high level of success since I left.

My initial task at LLNL was to coordinate scientific work with the new petawatt CPA laser. This was an impressive laser achievement involving a 1m diameter diffraction grating compressor incorporated in one of the 10 beams Nova. The project team was most ably led by Mike Perry. The PW laser was operated in short campaigns of a few weeks interleaved with normal operation of Nova. It was difficult to bring all the new technology quickly to an operational state for each new campaign but the experiments were in a truly novel regime and therefore exciting. Regrettably the PW laser was operated for only 3 years before Nova was closed down to transfer resources to construction of NIF and it was therefore never possible to fire the PW beam into an implosion in the 10 beam chamber as originally planned for fast ignition research.

Our team effort was first directed towards fast ignition – a new ICF ignition concept pioneered theoretically at LLNL by Max Tabak and colleagues. A rather abrupt shift of PW laser priorities was implemented by Mike Campbell after one year. The new goal advocated by Mike Perry, was MeV radiography for defense applications aimed at securing a new large scale project to replace the relativistic electron beam radiography machines used for MeV radiography in nuclear weapons research. This was a culture shock for me having never been in such a directed research environment. The goal proved to be impractical, an illustration perhaps of the tendency of advances in research not to be planned. The science results from the PW laser included significant new observations. The most outstanding was the unplanned discovery and subsequent characterization of laser generated proton beams resulting from installation of a radiochromic film diagnostic behind the target by a research student Richard Snively, whose motivation was to check reports from experiments at the CLF of collimation of high energy electrons.

With the PW laser closed down I began an effort to re-launch fast ignition research with some ideas for new diagnostics of energy transport by relativistic electrons. This was a collaborative venture with General Atomics Rich Stephens and University participation from Rick Freeman who was the Chair of applied Science at UC Davis. We had found that we could work very well together during the PW experiments and we attracted new funding from the Office of Fusion Energy science OFES and developed the research through collaboration with colleagues in Europe and Japan.

There were problems at LLNL with the cost escalation in the NIF project resulting in an abrupt major change in the management. First Mike Campbell and later Joe Kilkenny left LLNL. I was then in a situation where I did not know the new leaders George Miller and Ed Moses who were not from the laser ICF community and they did not know me. It took a while till we began to have mutual confidence and then I was appointed as Director of Petawatt Science for NIF programs. Short pulse high energy density science was given priority in the US at the level of the Presidents Office of Science and Technology Policy (OSTP) and I promoted a short pulse science and technology initiative at LLNL leading to expanded science R&D on PW laser applications and to the NIF advanced radiography capability (ARC) project to adapt initially one beam line of NIF for high energy PW operation.

With the Nova PW closed down we had been fortunate in finding generous collaborators at the CLF , the LULI laboratory and the ILE Osaka with whom we conducted the fast ignition research (Peter Norreys, Kazuo Tanaka and Ryosuke Kodama , Dimitri Batani , Michel Koenig and Francois Amiranoff). I also organized larger scale experiments covering several HED science goals including fast ignition, which were carried out through contractual access to the CLF PW and 100 TW lasers. Several 6 week cycles of laser access were granted to LLNL in exchange for the transfer of surplus Nova components to support laser upgrades at the CLF. Both the FI and wider HED science work was fruitful . OFES support for FI grew. The collaborative participation in FI research within the US expanded to include Ohio State University and UC San Diego . OFES also funded a new Fusion Science Center for study of High Energy Density States of Matter and Fast Ignition led by Riccardo Betti at the University of Rochester , linking six universities with facilities at the National Laboratories .

A new era is now starting in the US which LLNL once again has its own PW class laser Titan, combining one long pulse 1kJ beam and one CPA beam with new dielectric compression gratings capable of 400J pulses . A new PW capability is being commissioned at the Z Beamlet laser at SNL , LLE is constructing a major high energy CPA addition to Omega in the Omega EP project which has twin 2.5kJ CPA beams for injection into the 60 beam implosion facility . In Japan ILE is constructing Firex , a 10kJ CPA capability added to the 12 beam implosion facility . In Europe the CLF PW laser will soon be complemented by a French PW laser at LULI and a German PW laser at GSI . The LIL prototype of the French ignition facility LMJ, will have a multi PW beam added to its 8 long pulse beams. The PW lasers will support the development of scientific understanding in what is a very complex field of high intensity laser plasma interaction physics. Omega EP and Firex will enable larger scale integrated FI experiments that will determine whether NIF or LMJ in France will be adapted for full scale fast ignition. Current European discussion of a new European laser project Hyper could lead to a third option for full scale fast ignition.

4. Conclusion

In future I shall participate at a gentler pace more in the science and less in the management. I made another transition in Oct 2005 to a 1000 hours per year semi - retired status as a 65 year old Senior Scientific Advisor on PW science at LLNL . Regarding my past work in the UK I salute the outstanding achievements of the many friends, RAL colleagues, UK university and foreign collaborators that I have had the pleasure of working with as well as of those of the extensive CLF user community whose independent work largely built the reputation of the CLF. I have specially enjoyed always being able to work with PhD students. I look forward to seeing the progress of the next generation of scientists in our field and I hope to be able to give some modest assistance and advice to some of them. ICF ignition will be a major milestone that should be demonstrated with NIF and LMJ. Fast ignition may offer a route to higher gain and fusion energy but many scientific hurdles must be overcome before that could occur. It will be interesting to see what happens and I hope the new younger leaders and participants will find as much fun and excitement as I have had.

¹ A Gibson and M H Key, High Power Lasers, Reports on Progress in Physics
,43,1(1980)

² M H Key and R J Hutcheon , Spectroscopy of Laser Produced Plasmas , Rep .Prog
Phys. 16,201,(1980)

³ M H Key . Energy Transport in Laser Produced Plasmas , in Handbook of Plasma
Physics , Vol 3 , p 575 , A Rubenchik and S Witkowski Eds. Publ . North Holland
(1991)

⁴ M H Key Laboratory production of X-ray lasers, Nature 316, 314, (1985)

This work was performed under the auspices of the U.S. Department of Energy
by University of California, Lawrence Livermore National Laboratory under
Contract W-7405-Eng-48.